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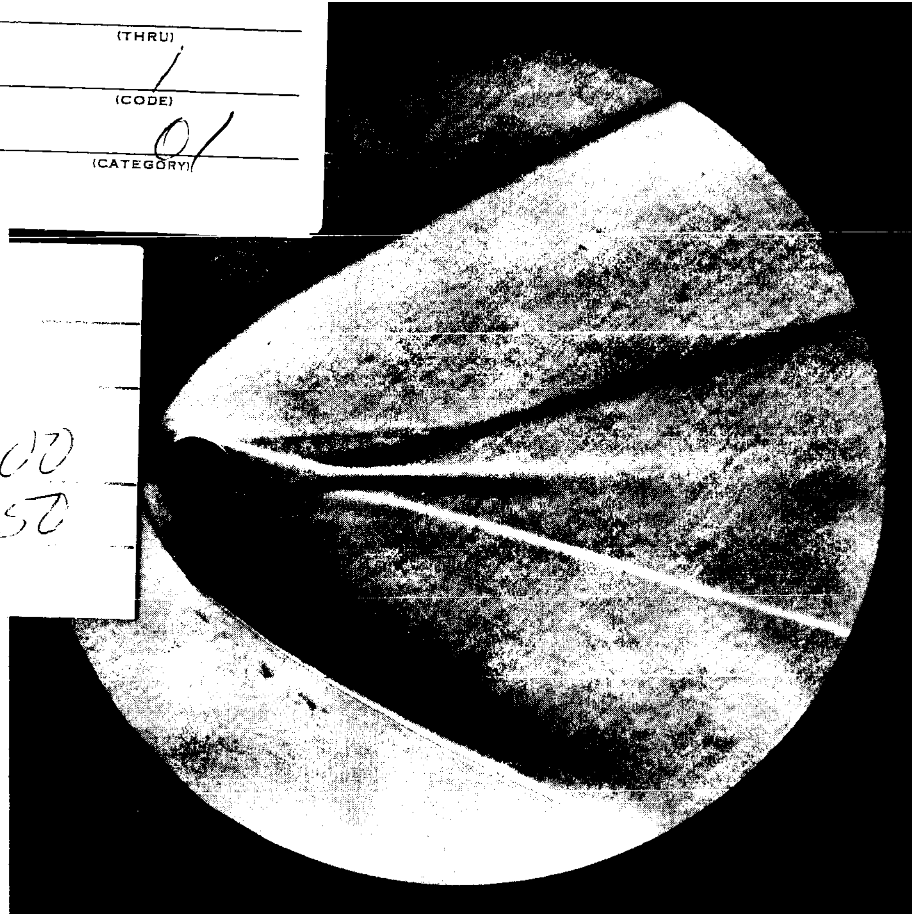

FLIGHT SCIENCES DEPARTMENT

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Summary Report— Study of Flow Fields About Axisymmetric Blunt Bodies at Large Angle-Of-Attack

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SUMMARY REPORT

STUDY OF FLOW FIELDS ABOUT AXISYMMETRIC BLUNT BODIES AT LARGE ANGLE-OF-ATTACK
(Contract NAS9-3159)

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FOREWORD

This document represents a summary report prepared for the Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas for the study conducted between July 1964 and November 1965 by the Space and Information Systems Division of North American Aviation, Inc., under Contract NAS9-3159, Study of Flow Fields About Axisymmetric Blunt Bodies at Large Angle-of-Attack. The work was conducted by the Flight Sciences Department.

The objective of the contract was to develop an IBM 7094 computer program to solve equilibrium real gas flow fields over blunt axisymmetric bodies at large angle-of-attack traveling at supersonic speed. The engineering analysis is documented in a separate Final Report, SID 65-1353; and the computer program is documented as a separate Computer Program Operating Manual, SID 65-1355.

INTRODUCTION

The prediction of flow fields about blunt bodies traveling at supersonic speed has long been one of the most challenging and important problems in aeromechanics. The significance of the problem is that for spacecraft entering a particular atmosphere the prediction of both heat transfer and aerodynamic forces depends on the results of a flow field calculation. Another subject requiring flow field predictions as input data is that of plasma-related communication problems such as radio blackout. The ability to make accurate flow field calculations for the Apollo Command Module, as well as other configurations, will lead to a significant advancement in the current state of the art of describing the entry environment and will aid in the analysis of experimental data obtained from model and flight tests.

Considerable progress has been made during the past decade on the inviscid blunt body problem; however, most methods have been limited to the zero angle-of-attack case for axially symmetric or two-dimensional shapes. The work conducted under contract to NASA/MSC by AVCO Corporation (Reference 1) represents the first solution valid for large angle-of-attack. Several restrictive assumptions were made, however, in its formulation. The analysis utilized the one-strip method of integral relations which introduced an approximation into the variation of properties across the shock layer. The second major assumption was that the properties varied in a simple sinusoidal manner in the circumferential direction about the stagnation point. It was the intent of the current contract effort to develop an improved method for blunt body flow calculation for large angle-of-attack. Such a method allows computation of the subsonic-transonic flow regions and permits definition of the initial conditions required to initiate a three-dimensional method-of-characteristics solution for the supersonic flow field.

STUDY OBJECTIVES

The contract objective was to develop an IBM 7094 computer program that will compute equilibrium real gas, inviscid flow fields over blunt axisymmetric bodies at large angles-of-attack traveling at supersonic speed. The solution obtained must calculate the state and motion variables in the subsonic and transonic region of the flow between the detached shock wave and the body surface. The program must be capable of generating sufficient supersonic data to allow a three-dimensional method-of-characteristics solution to be started for calculation of the supersonic flow.

The study was to start with a theoretical analysis of the complete equations describing the inviscid flow of equilibrium real air. A minimum number of assumptions was to be made to reduce the analysis to a method suitable for development into a computer program. Specifically, the resulting solution was to be a higher order approximation to the flow properties than that outlined in Reference 1. No a priori assumption was to be made that the body entropy is the maximum entropy in the shock layer. It was also a requirement that if an inverse technique were adopted, the program must automatically alter the shock shape until the desired body shape is obtained.

The computer program was to be capable of solving for the flow field about the Apollo Command Module and a generalized class of body shapes without surface discontinuities. The flow medium was to be either a perfect gas (any specific heat ratio between 1.0 and 1.67) or real air in chemical and thermodynamic equilibrium. In anticipation of the future use of the program in connection with general planetary atmospheres or high temperature test facilities, it was to be possible to replace the real air routine with the equilibrium properties of other gases. The angle-of-attack range was to be from zero to at least 40°.

The computer program was to be compatible with the IBM system at NASA/MSC, which consists of an IBM 7094-7040 system with the 7040 operating as a satellite system to the 7094. The program was to be written in FORTRAN IV source language and demonstrated to compile and run successfully on the MSC computer for three sample problems.

Detailed flow field data output was required with mandatory output of local shock wave standoff distance, body surface properties, stagnation point location, and streamline traces in the pitch plane and on the body surface. Additionally, properties throughout the shock layer must be output according to three special formats which may be selected at the user's option.

METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

Following a review of the state of the art in blunt body flow field prediction, it was concluded that the direct approach using the streamline curvature method, as exemplified by Reference 2, would not yield satisfactory detail in the stagnation region and would be difficult to formulate with automatic iteration. The direct method using integral relations was not considered to furnish sufficiently accurate flow field detail short of an unacceptably complicated multistrip analysis. The analysis of Bohachevsky et al. (Reference 3) is a promising new approach to the direct method of solution that was presented subsequent to this method evaluation. The inverse method is relatively straightforward and yields good detail throughout the flow field including the stagnation region. The disadvantage of having inherent integration instability appeared to be offset by the knowledge that smoothing can overcome the difficulty for zero angle-of-attack flow (Reference 4). The disadvantage of requiring an initial estimate of the shock shape is characteristic of the inverse method, but can be minimized by using an automatic iteration technique to improve the shock to obtain the desired body shape. On the basis of these considerations, the inverse method was adopted as the basic approach.

In the formulation and program development of this procedure, the following assumptions were made:

1. The solution was obtained by finite difference methods. That is, the solution was computed at each grid point of a three-dimensional array of points defined in a body oriented cylindrical coordinate system (r, θ, x).

2. The detached shock wave was represented by an analytic expression of the form

$$S(r,\theta) = S_0(r) + S_1(r) \cos \theta + S_2(r) \cos 2\theta$$

where

S is the x coordinate of the shock at radius r and meridian angle θ (measured from the pitch plane, which includes the body axis of symmetry and the free stream velocity vector). $S_0(r)$, $S_1(r)$, and $S_2(r)$ are polynomials in r, which in total do not exceed 20 terms and which use terms up to the order r^{20}.

3. Equilibrium air properties were represented by the empirical equations of Reference 5. These analytical fits were stated to have an average error of less than 1 percent when compared to the best computed data, Reference 6.

4. The detached shock wave from which the automatic iteration technique starts must be sufficiently close to the correct shock that predicted body coordinates vary linearly with changes in the shock fit coefficients.

The flow field program integrates the basic state and flow properties starting from the shock until the entire subsonic-transonic flow field and the predicted body are obtained. The integration is performed from the shock in a sheared cylindrical coordinate system since the initial conditions are most easily found immediately behind the shock. The inherent instability is overcome by data smoothing conducted in two directions. Steps are included to minimize any possible distortion of data by the smoothing procedure. The body surface is found from a routine in the computer program that also automatically drops grid points that lie inside the body (where singularities can result in erratic flow properties). This procedure also tests for two additional types of singularities.

The automatic correction of the detached shock shape to obtain the correct body shape is done by using an influence coefficient technique. A set of body control points equal in number to the number of shock coefficients is selected that, after convergence, lie on the correct body shape. Each shock coefficient in turn is perturbed a small amount while the change in the predicted body coordinates at the control points is noted. Following the assumption of linearity, a set of simultaneous algebraic equations is then solved for the corrections to be applied to the shock coefficients.

BASIC DATA GENERATED AND SIGNIFICANT RESULTS

Flow fields were developed for four blunt body shapes. Two of these shapes, Apollo and Gemini, are of the capsule type while the other two are a sphere and spherically blunted cone-cylinder. The flight conditions employed for each of these cases are shown in Table 1.

Table 1. Flight Conditions for Blunt Body Cases

Shape	Angle of Attack (Degrees)	Flight Altitude (Feet)	Flight Velocity (Feet/Second)	Type of Air Media
Sphere	40	69,136	9,803	Perfect Gas $\gamma = 1.4$
Apollo	22	150,480	22,754	Real Gas
Gemini	15	175,200	20,942	Real Gas
Spherically Blunted Cone-Cylinder	0	250,000	35,000	Real Gas

Ambient air properties for the above flight conditions were obtained from the 1962 Standard U. S. Atmosphere. The sphere case was used solely for the purpose of verifying the computer program logic and functional operation. The other three cases, with their specified free-stream flight conditions, were contractual objectives.

The advantage of the sphere shape as a checkout case is its easily attainable angle-of-attack shock shape. The shock for the zero angle-of-attack blunt body case is well known and can readily be rotated to give an accurate angle-of-attack shock. It was found during the course of this study that the angle-of-attack shock shape, not only on the sphere but on the other body shapes as well, could be adequately defined by a polynomial expression in cylindrical coordinates containing symmetric terms, cosine θ terms, and cosine 2θ terms. An eight coefficient shock graphically fitted in the $\theta = 0°$, $\theta = 90°$, and $\theta = 180°$ meridian planes was adopted for the sphere case. A graphical comparison of the shock was made in the $\theta = 45°$ and $\theta = 135°$ meridian planes with excellent results being obtained. In summarizing, for the sphere case it can be noted that the angle-of-attack sphere flow field developed by the program thoroughly checks with the zero angle-of-attack solution at the same spatial location in the flow field.

One problem area that occurred in this study in all of the cases investigated pertains to singularities that arise during the numerical computation of the flow fields. Two known singularities arise from the particular choice of the coordinate system and are removable by a reorientation of the problem to a new coordinate system. One singularity appears when the coordinate plane (i.e., marching plane) becomes aligned with the local characteristic line at a point in the flow field. The other appears when the marching plane becomes aligned with the local streamline slope.

Fortunately, both of these computational difficulties nearly always occur in the immediate vicinity of the body and are overcome by extrapolating directly through the singular region to obtain the body location and flow properties. The expected presence of inherent instability in the flow field properties was verified and successfully overcome by using a smoothing procedure.

Perhaps the most significant single accomplishment achieved in this study was the generation of an angle-of-attack Apollo flow field. The resulting body shape closely approximates the true Apollo shape giving excellent agreement in the difficult shoulder region. As expected, the Apollo pressure distribution generated by the program is noticeably different from the Newtonian distribution except in the vicinity of the stagnation point. A nineteen-coefficient polynominal expression is required to define the shock. A hand iteration technique was also developed for the Apollo shape for systematically arriving at a shock shape that is within the limitations of the influence coefficient automatic iteration procedure. One fact that became evident in using the program to generate the Apollo angle-of-attack flow field was the increased run time and reduced integration step size compared with the zero angle-of-attack flow field. The large property gradients in the windward shoulder region necessitated using the reduced integration step size to maintain stability of the integration procedure.

The development of a Gemini angle-of-attack solution was similar to the Apollo case. Since the program is unable to work with a sharp corner, as is the case for the true Gemini body, it becomes necessary to artificially add a small shoulder radius in order to obtain the Gemini solution. This does not affect the validity of the greater part of the flow field results.

The last body shape, a spherically blunted cone-cylinder at zero angle-of-attack, exhibits some rather interesting results. The nose radius is small compared to the maximum body diameter and the half cone angle is 60°. The shock shape that results is geometrically somewhat similar to the body shape in that it is nearly conical over the body face except near the axis where it is nearly spherical. The mass flow that crosses the shock near the axis where it is nearly normal to the free stream will of course undergo a higher entropy increase than the flow that crosses the weaker, more conical shock front. This high entropy flow lies mostly in a layer adjacent to the body surface in the shock layer, and will have a lower Mach number than the flow at approximately the same pressure just outside of the high entropy layer. Thus the sonic line in the entropy layer will be located in a lower pressure region (nearer the shoulder). The three-dimensional character of the flow dictates that this layer will be thinned out approximately as $1/r$ so that near the shoulder this layer is of the order of 2% of the shock layer thickness. To detect this thin layer near the shoulder with the flow field program, the integration step size would have to be a fraction of the entropy layer thickness. The step size used for this sample case was about 3% of the shoulder standoff distance, so that it was not expected that the results would detect the entropy layer near the shoulder. This expectation was substantiated by the program results, which predicted a body sonic location at a radius about half the maximum body radius. In fact, however, the inverse method can define the entire sonic line correctly provided that a sufficiently small integration interval is chosen. It should also be noted that smoothing to maintain stability in the property data is not necessary for this body shape, because the angle-of-attack is zero.

In summary, the results obtained with the program appear to agree quite well with other available published theoretical information. In addition, flow patterns on the Apollo and Gemini surfaces appear consistent with published experimental oil flow data.

LIMITATIONS OF THE ANALYSIS

Certain limitations of the analysis are related to the basic assumptions originally adopted in the analysis, while other limitations are inherent in the detailed formulation. The following list summarizes the major limitations:

1. The grid network used in the finite difference scheme is limited to a matrix of 300 points for each location of the marching plane. Up to 15 radii values and 20 meridian angles (not necessary equally spaced) may be used.

2. Although the flow field integration procedure used in the program is not restricted to axially symmetric bodies, the analytic shock fit currently in the computer program may require modification to include higher order terms in the meridian angle θ to correctly represent the more complicated shock shapes expected for non-axially symmetric bodies. In any event, the shock fit equation can be extended by straightforward programming procedures and is not a fundamental limitation in the analysis.

3. The program is limited to real air in chemical and thermodynamic equilibrium or a perfect gas. For a perfect gas the lower limit of γ, the specific heat ratio, is 1.0. The upper limit is not defined, but exceeds the requirement of 1.67.

4. Free stream conditions are not limited for perfect gas flows, but for real equilibrium air flows the program is limited to a density range from 10^{-6} to 10^{2} relative atmospheres (ρ/ρ_0) where $\rho_0 = 2.5089 \times 10^{-3}$ slug/ft^3, and to temperatures up to 15,000K.

5. In the use of the iterative convergence technique:

   a. The body shapes are limited to a generalized class of axially symmetric bodies with or without hemispherical blunting, and the specific Apollo Command Module shape.

   b. The initial shock shape estimate must be sufficiently close to the correct shock that the influence coefficients expressing the shock shape and body coordinate corrections are used in the linear range.

6. Angle-of-attack is limited to 40°. This limit is fundamental and results from the probable location of the sonic line on the body when the coordinate system is body-oriented.

IMPLICATIONS FOR RESEARCH

The successful development of a computer program for high angle-of-attack blunt body flow field prediction furnishes the gasdynamic analyst with a new and powerful tool. Being based on a minimum number of asumptions, the analysis will furnish highly accurate theoretical results which may be used for the following research subjects:

1. By suitable use of the cutoff flow field program capability a very detailed analysis may be made of a small flow field region such as the stagnation point. This information will be valuable in studying the behavior of the stagnation line in comparison with analytical predictions and for the study of flow field behavior around small radius shoulders where high property gradients occur.

2. Body and flow field property distributions can be used to verify and complement existing experimental data and make predictions for test conditions now beyond the range of test facilities or free flight testing.

3. The computer program will allow accurate calculation of aerodynamic plasma sheath and heat transfer characteristics for advanced entry vehicle studies, including (after introduction of appropriate thermodynamic data) entry into other planetary atmospheres.

SUGGESTED ADDITIONAL EFFORT

The following topics are suggested for further study to improve the program speed, accuracy, and capability (the topics are not necessarily listed in the order of their importance).

1. Improved Program Efficiency to Reduce Computer Running Time

   a. Study analytically and experimentally (through exercise of the program) the use of integration step size control, as well as alternate integration procedures.

   b. Review the organization of the computer program and rework to improve general efficiency.

   c. Evaluate the need for double precision currently used in the computer program.

   d. Study the possibility of eliminating (or reducing) the need for smoothing by use of analytic data interpolation on inner radii grid points.

2. Increased Program Accuracy

   a. Improve the method of finding body coordinates in the pitch plane, and possibly change the integration variable for stream function to improve accuracy.

   b. Study filtering techniques both analytically and experimentally to determine the type and amount of coupling to finite-difference mesh size. Study basic error sources such as end of array errors, etc., in relation to smoothing to develop better understanding of fundamental behavior of the three-dimensional analysis.

3. Additional Program Capability

   a. Examine the iterative convergence procedure and define possible improvements using advanced optimization techniques, to extend capability.

   b. Establish compatibility of the data output with three-dimensional method of characteristics program input requirements.

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